

# Measuring differential rotation of the K-giant $\zeta$ And<sup>★</sup> (Research Note)

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## ABSTRACT

**Aims.** We investigate the temporal spot evolution of the K-giant component in the RS CVn-type binary system  $\zeta$  Andromedae to establish its surface differential rotation.

**Methods.** Doppler imaging is used to study three slightly overlapping spectroscopic datasets, obtained independently at three different observing sites. Each dataset covers one full stellar rotation with good phase coverage, and in total, results in a continuous coverage of almost three stellar rotations ( $P_{\text{rot}} = 17.8$  d). Therefore, these data are well suited for reconstructing surface temperature maps and studying temporal evolution in spot configurations. Surface differential rotation is measured by the means of cross-correlation of all the possible image pairs.

**Results.** The individual Doppler reconstructions well agree in the revealed spot pattern, recovering numerous low latitude spots with temperature contrasts of up to  $\approx 1000$  K with respect to the unspotted photosphere, and also an asymmetric polar cap which is diminishing with time. Our detailed cross-correlation study consistently indicate solar-type differential rotation with an average surface shear  $\alpha \approx 0.055$ , in agreement with former results.

**Key words.** stars: activity – stars: imaging – stars: late-type – stars: starspots – stars: individual:  $\zeta$  Andromedae

## 1. Introduction

Stellar activity involves a range of magnetic activity phenomena, which are generated and modulated by the dynamo mechanism. The differential rotation is of utmost importance in understanding the magnetic activity, since it is a key element of the stellar dynamo, which has a controlling influence over the strength of magnetic fields generated, and thus that of the activity itself. The differential rotation on stars with convective envelopes puts constraints on the large scale topology of the magnetic field, therefore giving important information on the working of the dynamo beneath the surface. Nevertheless, on stars the detection of the surface differential rotation still remains a challenging observational task, since stellar surfaces, except in rare cases (e.g., Gilliland & Dupree 1996, Monnier et al. 2007), cannot yet be resolved directly. Thus, indirect surface reconstruction technique, like Doppler imaging (see, e.g., Vogt et al. 1987, Piskunov et al. 1990), is needed. Moreover, since starspots are commonly regarded as tracers of photospheric plasma motions, the pattern of surface differential rotation can be evolved by investigating

short-term spot redistribution through reconstructed time-series surface images (e.g., Donati & Collier Cameron 1997, Weber & Strassmeier 2001, Kővári et al. 2004, 2007a, Barnes et al. 2005, Hussain et al. 2006, Weber 2007, etc.).

In this work the differential rotation of the K-giant component in the long-period RS CVn binary  $\zeta$  Andromedae (hereafter  $\zeta$  And) is studied.  $\zeta$  And (HD 4502) is a single-lined spectroscopic binary with a bright ( $V = +4.1$  from SIMBAD) K-giant ellipsoidal variable component (Campbell et al. 1911), and an unseen companion of likely late-G or early-K dwarf (Kővári et al. 2007b, hereafter Paper I, see also the references therein). Although, its photometric variability is ruled by the ellipticity effect, light curve modulation with the rotational cycle of 17.8 days is also present, suggesting spot activity (cf. Strassmeier et al. 1989). This feature is in agreement with the strong Ca II H&K emission reported first by Joy & Wilson (1949). The star is known also from its H $\alpha$ , UV, and X-ray activity (cf. Eaton 1995, Reimers 1980, and Schrijver et al. 1984, respectively).

The first extended study of the target using photometric modelling and Doppler imaging was presented in Paper I. Doppler maps revealed spots dominating at lower to medium latitudes with a typical temperature contrast of  $\approx 750$  K, as well as a weak and variable polar cap. Considering the distorted geometry, the fundamental system and stellar parameters were specified and an investigation for differential rotation was presented.

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<sup>★</sup> Based on observations collected using the Bernard Lyot Telescope at Pic du Midi Observatory; the 1.93-m telescope at Haute-Provence Observatory, France; and the 8.2-m Kueyen telescope (VLT/UT2) of the European Southern Observatory, Chile (Prg. 081.D-0216(A)).

Recently, Korhonen et al. (2010, Paper II from here on) measured the angular diameter of the star with the Very Large Telescope Interferometer (VLTI/AMBER) and specified its absolute dimensions. A new Doppler image was also reconstructed from the high quality spectra obtained simultaneously from the VLT/UVES instrument. The resulting image, similarly to the ones in Paper I, recovered mainly cool spots at lower latitudes, amongst with the most dominant features concentrating at quadrature positions, and also some polar features, but with significantly weaker contrast.

A unique opportunity presented itself during August and September 2008, when the star was measured almost consecutively from Pic du Midi Observatory (France), from Haute-Provence Observatory (France), and from the European Southern Observatory (Chile, see Paper II), providing three independent (slightly overlapping) spectroscopic datasets, each of them suitable to reconstruct one single Doppler image using four favorable mapping lines. In Sect. 2 a brief review of the three datasets is given, then, in Sect. 3, the results from Doppler imaging are presented. Afterwards, in Sect. 4 the Doppler maps are compared with each other by using our sophisticated cross-correlation technique to search for the surface differential rotation pattern. Finally, the results are summarized and discussed in Sect. 5.

## 2. Spectroscopic observations

The spectroscopic data were collected at three different observing sites independently, between 13 August and 1 October, 2008. Each dataset covers roughly one stellar rotation (16–18 days) and the consecutive sets overlap one another by 1–2 days. In all the three cases, the covered wavelengths include the 6400 Å region commonly used for Doppler imaging. This contains, amongst others, the mapping lines Fe I-6411, Fe I-6421, Fe I-6430 and Ca I-6439. The summary of the observations is given in Table 1.

All the spectra are phased using the same ephemeris as in Paper I, fitting the zero phase to the conjunction with the secondary in front:

$$\text{HJD} = 2\,449\,997.223 \pm 0.017 + 17.769426 \pm 0.000040 \times E. \quad (1)$$

### 2.1. NARVAL spectra

The first dataset in the time-series with altogether 48 spectra was obtained during 10 nights between 13–31 August at Pic du Midi Observatory (France) using the 2-m Bernard Lyot Telescope, equipped with the NARVAL spectrograph (Aurière 2003). The spectrograph covers the wavelength range between 3700 Å and 10000 Å with a resolving power ( $\lambda/\Delta\lambda$ ) of 60 000. Each observation consists of four 30 s long exposures obtained immediately after each other. These exposures were combined into one observation to increase the signal-to-noise ratio (S/N). This way 10 individual observations (one per night) from different rotational phases were obtained. The information in Table 1 is for the combined observations. The reference HJD of the Doppler map calculated from the NARVAL spectra in Sect. 3 (i.e., the mean HJD) is 2454702.088.

### 2.2. SOPHIE spectra

The second set consisting of 10 spectra were collected between 30 August and 15 September, 2008 with the SOPHIE échelle

**Table 1.** Observational records of our spectroscopic data.

HJD 2454000+	phase <sup>a</sup>	S/N	date (2008)	instrument	<i>n</i> <sup>b</sup>	<i>t</i> <sub>exp</sub> <sup>c</sup> [s]
691.5464	0.178	446	13 Aug	NARVAL	4	30
696.5723	0.461	258	18 Aug	NARVAL	4	30
699.6046	0.632	242	21 Aug	NARVAL	4	30
701.5989	0.744	679	23 Aug	NARVAL	4	30
702.5645	0.798	384	24 Aug	NARVAL	4	30
703.5135	0.852	270	25 Aug	NARVAL	4	30
704.5673	0.911	296	26 Aug	NARVAL	4	30
705.5435	0.966	329	27 Aug	NARVAL	4	30
708.6240	0.139	421	30 Aug	SOPHIE	1	120
708.6278	0.140	371	30 Aug	NARVAL	4	30
709.5420	0.191	445	31 Aug	SOPHIE	1	120
709.6025	0.194	291	31 Aug	NARVAL	4	30
710.5015	0.245	335	01 Sep	SOPHIE	1	120
711.6389	0.309	441	02 Sep	SOPHIE	1	120
714.6815	0.480	261	05 Sep	SOPHIE	1	120
715.6242	0.533	198	06 Sep	SOPHIE	1	950
717.4957	0.639	269	08 Sep	SOPHIE	1	120
718.5432	0.698	441	09 Sep	SOPHIE	1	120
720.5707	0.812	237	11 Sep	SOPHIE	1	166
722.8167	0.940	866	13 Sep	UVES	3	8
724.5445	0.035	258	15 Sep	SOPHIE	1	120
724.7046	0.046	650	15 Sep	UVES	3	8
726.7101	0.159	586	17 Sep	UVES	3	8
727.6870	0.214	628	18 Sep	UVES	3	8
728.7387	0.273	762	19 Sep	UVES	3	8
730.7203	0.384	693	21 Sep	UVES	3	8
732.7287	0.497	914	23 Sep	UVES	3	8
734.6517	0.606	785	25 Sep	UVES	3	8
736.6936	0.721	612	27 Sep	UVES	3	8
740.7533	0.949	802	01 Oct	UVES	3	8

**Notes.** <sup>(a)</sup> Phases computed using Eq. 1. <sup>(b)</sup> Number of exposures combined into a final spectrum. <sup>(c)</sup> Lengths of the single exposures.

spectrograph (Perruchot et al. 2008) at the 1.93-m telescope of Haute-Provence Observatory (France). The spectrograph has a wavelength range of 3872–6943 Å. The observations were carried out in the high efficiency mode (HE) using 100 μ fibre, which gives  $\lambda/\Delta\lambda$  of 40 000. The exposure time was usually 120 s, but in two cases longer times were used: on September 6 the exposure time was 950 s and on September 11 166 s. The mean HJD of the SOPHIE observations is 2454715.177.

### 2.3. UVES spectra

The third set of observations were carried out at the European Southern Observatory (Chile) with UVES (UV-Visual Echelle Spectrograph, Dekker et al. 2000) spectrograph mounted on 8.2-m Kueyen VLT unit telescope. The data were collected during ten nights between 13 September and 1 October, 2008. In the observations the red arm standard wavelength setting of 600 nm was used with image slicer #3. This configuration gives a resolving power ( $\lambda/\Delta\lambda$ ) of 110 000 and a wavelength coverage of 5000–7000 Å. For every observation the three 8 s exposures obtained immediately after each other were combined into a single, very high S/N spectrum. For further details see Paper II. Computing the average HJD we get 2454730.621.

### 3. Doppler imaging with $\text{TEMPMAP}_\epsilon$

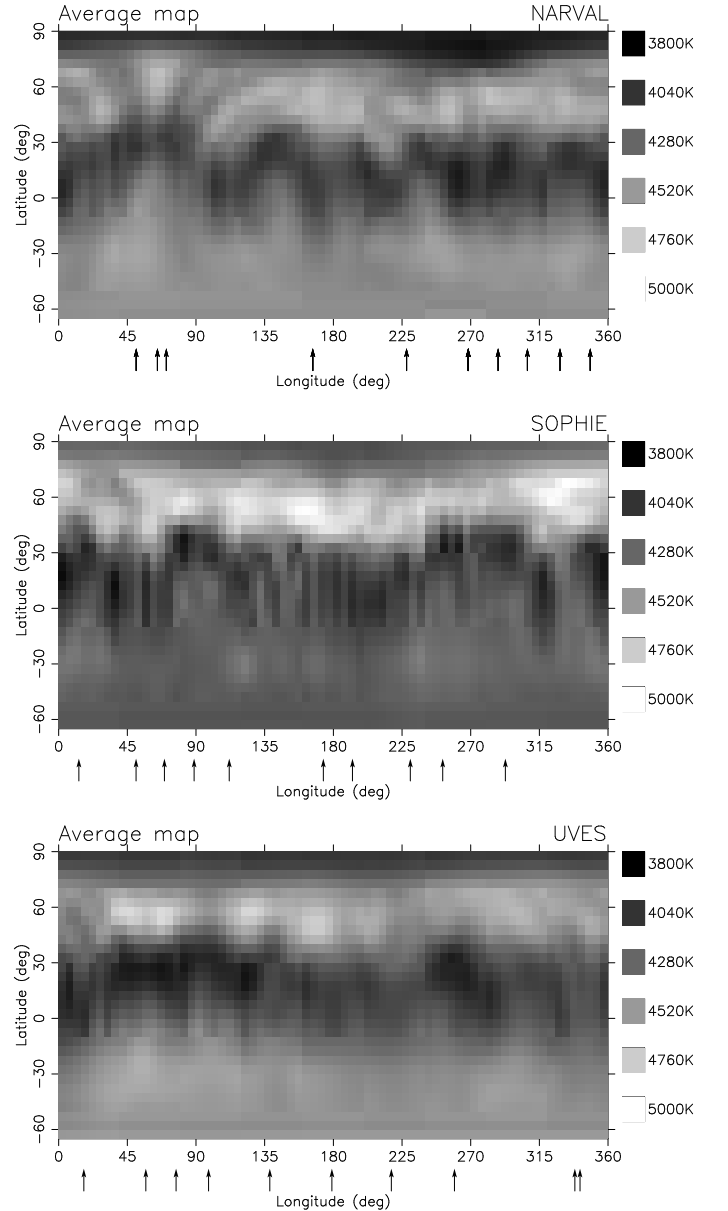
All of the three datasets cover roughly one stellar rotation, and thus allow to reconstruct one Doppler image for each set. For the surface image reconstruction we started from the Doppler imaging code  $\text{TEMPMAP}$  (Rice et al. 1989) which, afterwards, was extended by us ( $\text{TEMPMAP}_\epsilon$ , Paper I) to take into account the non-spherical shape of stars in close binary systems. In our approximation, the real Roche-geometry is simplified to a rotation ellipsoid, that is elongated towards the other component. We note here that  $\text{TEMPMAP}_\epsilon$  is the only Doppler imaging code available so far, that can use non-spherical surface geometry. We also note, that neglecting the ellipticity in the Doppler reconstruction would yield a significant rise in the goodness-of-fit value of the line profile inversion (see Papers I-II). Eventually, the astrophysical input data of  $\zeta$  And, including the most feasible distortion parameter, are adopted from Paper I (Table 2 therein).

Doppler imaging was performed for a sample of well known mapping lines, that usually produces the most reliable outcome. In practice, we use only those lines that are jointly covered by all the three datasets: Fe I-6411, Fe I-6421, Fe I-6430 and Ca I-6439. The resulting Doppler images are plotted in Fig. 1. Albeit a higher resolving power would allow for a larger amount of grid points to be used in the map, for the comparison reasons we apply the same grid size of  $5^\circ \times 5^\circ$  in all the maps. The individual reconstructions well agree in the revealed spot pattern, i.e., numerous low latitude spots are recovered with temperature contrasts of up to  $\approx 1000$  K with respect to the undisturbed photosphere of 4600 K. In addition, an asymmetric cool polar feature is also present at around  $\phi \approx 0.75$ , however, switching from the NARVAL map to the SOPHIE and UVES maps, i.e., from August to September 2008 the contrast became weaker and the spot concentration shifted backwards in phase. We refer also to Paper II, wherein, using the UVES observations, a thorough Doppler imaging study was carried out.

### 4. Cross-correlation study

Surface differential rotation (DR) of a spotted star can be measured by cross-correlation of subsequent Doppler images (Donati & Collier Cameron 1997). Nevertheless, even when having reliable Doppler images, short-term spot changes (e.g., vivid interaction between neighbouring spots, emerging a new spot or disintegrating an old one, etc.) can easily mask the trace of the surface DR in the cross-correlation function (hereafter ccf) map. To emphasize the DR pattern, and to diminish differences originating from individual spot motion and evolution, we use our newly developed cross-correlation technique ACCORD ('Average Cross-CORrelation of time-series Doppler images', see e.g., in Kővári et al. 2004, 2007a, Paper I). The basic idea of the method is, that averaging the more ccf maps, the better result can be achieved by boosting such cross-correlation features that are jointly present, like the DR pattern itself.

From the Doppler maps shown in Fig. 1 three cross-correlation pairs can be formed: NARVAL/SOPHIE (N/S), NARVAL/UVES (N/U), and SOPHIE/UVES (S/U). Those ccf maps then can be averaged. However, a simple averaging will not definitely boost the DR pattern, since the shape of the correlation pattern depends on the time gap between the paired Doppler images, i.e., the larger the time gap, the larger the elongation of the individual 1-D longitudinal cross-correlation functions parallel to the equator (in practice, these are longitude strips in bins of  $5^\circ$ , see, e.g., Kővári et al. 2004). Thus, to avoid fuzziness, a linear renormalization must be done before averaging. When



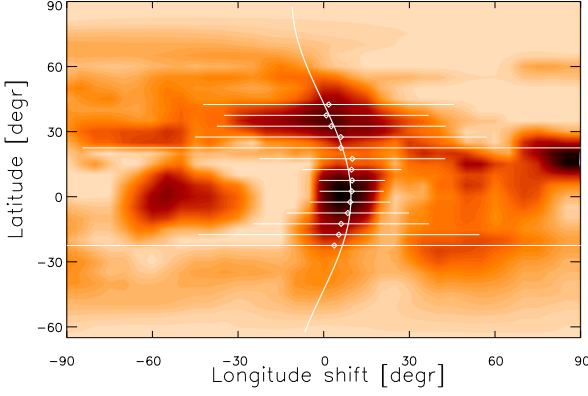
**Fig. 1.** From top to bottom: the combined (Fe I-6411+Fe I-6421+ Fe I-6430+Ca I-6439) Doppler maps in time series for the NARVAL, SOPHIE, and UVES data, respectively. Arrows underneath indicate the observational phases.

the final average ccf map is assembled, the best-correlating pattern can be fitted by an assumed form of the DR law. The result of applying ACCORD to the three Doppler images is plotted in Fig. 2. For the latitude ( $\beta$ ) dependent rotation law we assume the usual quadratic form of  $\Omega(\beta) = \Omega_{\text{eq}} (1 - \alpha \sin^2 \beta)$ , where  $\Omega_{\text{eq}}$  is the equatorial angular velocity and  $\alpha = (\Omega_{\text{eq}} - \Omega_{\text{pole}})/\Omega_{\text{eq}}$  is the dimensionless surface shear parameter. The best fit yields solar-type equatorial acceleration:

$$\Omega(\beta) = 20.763 (1 - 0.053 \sin^2 \beta) [^\circ/\text{d}]. \quad (2)$$

### 5. Discussions and conclusion

The outcome of our new cross-correlation study seems to be fairly consistent with the result in Paper I, where  $\alpha$  of  $0.049 \pm$



**Fig. 2.** Applying the ACCORD technique for the three available Doppler images plotted in Fig. 1. Better correlation on the resulting ccf map is represented by darker shade. The average longitudinal cross-correlation functions in bins of  $5^\circ$  are fitted by Gaussian curves (Gaussian peaks are indicated by dots, the FWHMs by horizontal lines). The continuous line represents the best fit quadratic DR law.

0.003 was derived. To test the reliability of our method and result we repeat the correlation study, but instead of using the combined Doppler images in Fig. 1, we start from individual reconstructions, i.e., we use Doppler images that are recovered individually for a single mapping line. This way we have four maps (Fe I-6411, Fe I-6421, Fe I-6430 and Ca I-6439) for each datasets (N, S, U), separately, thus 12 cross-correlations can be achieved and finally averaged. We expect that this way the signal-to-noise of the DR pattern in the ultimate average ccf map will improve. The result with the fitted DR pattern is shown in Fig. 3 yielding nearly the same DR law as of Eq. 2:

$$\Omega(\beta) = 20.689 (1 - 0.055 \sin^2 \beta) [^\circ/\text{d}], \quad (3)$$

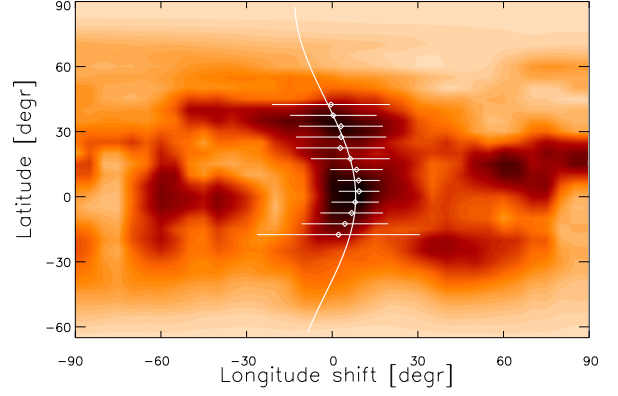
nevertheless, the relative height of the fitted ‘ridge’ in the ccf landscape (i.e., the maxima of the gaussian peaks) has significantly ( $\approx 40\%$  on average) risen, compared to the one in Fig. 2. We can also estimate the errors of the derived parameters given in Eq. 3 by carrying out the whole process, but with using only three mapping lines from the available four, i.e., we perform four cross-correlation studies separately and estimate the error bars from the  $1-\sigma$  of the obtained DR parameters, getting  $\varepsilon(\Omega_{\text{eq}}) = \pm 0.056^\circ/\text{d}$  and  $\varepsilon(\alpha) = \pm 0.0022$ . We consider this result as a proof of the reliability and robustness of the ACCORD technique. A comparative summary of the derived DR parameters is given in Table 2.

Theoretical calculations predict that across the H-R diagram DR becomes stronger with increasing rotation period and evolutionary status (Kitchatinov & Rüdiger 1999). Still,  $\zeta$  And shows

**Table 2.** Comparing the DR parameters

$\Omega_{\text{eq}}$ [ $^\circ/\text{d}$ ]	$\alpha$	LT <sup>a</sup> [d]	note
19.027	0.049	381	from Paper I
20.763	0.053	332	using combined images
20.689	0.055	315	using separate reconstructions

**Notes.** <sup>(a)</sup> Time needed by the equator to lap the pole by one full period.



**Fig. 3.** Applying the ACCORD technique for the individual Doppler reconstructions using Fe I-6411, Fe I-6421, Fe I-6430 and Ca I-6439 mapping lines, separately. Otherwise as in Fig. 2.

relatively weak surface differential rotation. This could be explained by large starspots not following the stellar surface flows, as they are anchored at different depth in the convection zone. Recent investigation by Korhonen & Elstner (2011) using dynamo models shows that the much weaker DR than what is used in the model is recovered when having only the large-scale dynamo field. The real input DR law can only be recovered when the model also includes small-scale fields. The question is whether or not large starspots can really be caused by small-scale magnetic fields.

According to Kitchatinov & Rüdiger (2004) giant stars in close binary system, e.g., RS CVn-type binaries, can also show anti-solar differential rotation, where the equator rotates slower than the poles. Such a DR law has been detected, for example, in  $\sigma$  Gem (Kővári et al. 2007a). Kitchatinov & Rüdiger (2004) attribute the anti-solar differential rotation to strong meridional flow, which could be caused by barocline driving due to large thermal spots or by field forcing of a close companion. In accordance with this, a poleward meridional flow has been reported for  $\sigma$  Gem with an average velocity of  $350 \text{ km s}^{-1}$  (Kővári et al. 2007a). On the other hand, no sign of such a meridional flow is seen on  $\zeta$  And (Paper I). This observed difference between  $\zeta$  And and  $\sigma$  Gem can be rooted in the different system geometry and dynamics (Kővári et al. 2012). Distortion and tidal forces could account for the converse DR in these two cool giants.

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